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Spatio-temporal parameters in infant's reaching movements are influenced by body orientation

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Abstract

Many studies have demonstrated that the seated position is more effective in promoting reaching movements when compared with supine. The aim of this longitudinal study was to verify the effect of seated and supine positions on spatio-temporal parameters of reaching in 4–6-month-old infants. Four infants were observed during reaching trials in both positions. A total of 235 reaches were analyzed by using the 3D movement reconstruction. Our results showed that frequency of reaching and straightness index increased over age. Significant differences between the positions were observed at 4 months, when the frequency increased and the duration and deceleration time decreased in the seated position. There were no significant differences at 5 and 6 months. These findings suggest that young infants are able to change kinematical parameters of reaching to adapt themselves to intrinsic and extrinsic constraints (i.e. age and position).

Keywords: Reaching; Kinematics; Body orientation; Supine; Seated

1. Introduction

In the last 20 years, researchers within the area of motor development have with increased frequency focused on the development process in an attempt to understand how infants adapt themselves to intrinsic and extrinsic constraints with regard to age (Clark & Whitall, 1989; Rosengen, Savelsbergh, & Van der Kamp, 2003; Van der Kamp, Oudejans, & Savelsbergh, 2003).

The concept of constraint was formulated by Newell (1986), who distinguished three categories of constraints which interactively determine the development of coordination, namely organismic, environmental and task constraints. Newell's formulation was supported by studies that attempted to understand the development of reaching and took into account approaches relying both on intrinsic constraints, like improvements in postural control in seated (Rochat & Goubet, 1995) and supine positions (Fallang, Saugstad, & Hadders-Algra, 2000); as well as extrinsic constraints, such as studies examining the use of objects with different sizes and rigidity (Rocha, Silva, & Tudella, 2006), objects

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in motion (Van Hof, Van der Kamp, Caljouw, & Savelsbergh, 2005) and different body orientations (Out, Van Soest, Savelsbergh, & Hopkins, 1998; Rochat, 1992; Savelsbergh & Van der Kamp, 1994).

Research on the influence of different body orientations during the reaching process has demonstrated that the seated position can increase the frequency and duration of successful reaching movements. Indeed, young infants (12–19 weeks), when placed seated showed similar frequency and duration of reaching to those of older infants (20–27 weeks) who were placed in either supine, reclined or seated position (Savelsbergh & Van der Kamp, 1994).

The results of this study raise important questions. We wonder if this similarity between younger and older infants can also be found for kinematic parameters (spatio-temporal variables) of reaching. In other words, can seated position improve reaching movements in younger infants in relation to kinematic parameters?

Accordingly, the purpose of the current study was therefore to verify whether and how different body orientations – related to the gravity vector – affect spatio-temporal variables of reaching kinematics in 4–6-month-old infants over age.

Two hypotheses are tested in this study. First, we predict that kinematic variables of reaching change between 4 and 6 months. We believe that 6-month-old infants are more skillful than 4-month-olds given their development of visual acuity, visual attention, cognitive processes and postural control (Fallang et al., 2000; Rochat & Goubet, 1995; Savelsbergh & Van der Kamp, 1994; Van Hof, Van der Kamp, & Savelsbergh, 2004, 2006). Thus, we expect that older infants, independent of their body orientation, have better reaching performances, i.e., straighter trajectory, shorter duration and higher velocity.

Our second hypothesis is that the seated position allows better reaching independent of age—not only regarding frequency and duration but also in terms of spatio-temporal parameters. Insights from biomechanics reveal that supine position demands higher muscular torque at the beginning of the reach, as the weight force vector position is farther from the longitudinal shoulder axis. By comparison, the seated position demands lower muscular torque at the beginning of the reach because the weight force vector position is closer to the longitudinal shoulder axis (Savelsbergh & Van der Kamp, 1994). In both cases, the weight force vector position must be considered when the movement begins with 0° shoulder and elbow flexions. Given the infants' inability to properly control their trunks, they are more affected by different body orientations, that is why the higher muscular torque demanded at the beginning of the reach would have an effect on the kinematics of movement. Moreover, in the supine position, the mechanics of the arm could be compared to an inverted pendulum, in which the center of mass is located above the rotational center, on the shoulder (Out et al., 1998). This configuration would lead to arm instability during reaching in the supine position and would compromise the quality of the reach.

Consequently, we suggest that young infants, when seated, experience less difficulty at the beginning of the movement due to the lower muscular torque demanded and therefore they show a straighter reaching trajectory. In spite of the fact that due to shoulder flexion the muscular torque demanded gets higher from the middle of the reaching trajectory to its end, the infant can touch the object by means of inertia (Out et al., 1998). When infants use these biomechanical advantages, the movement would be performed with straighter trajectory, shorter duration and higher velocity. In the supine position, the reaching trajectory would be less straight because of the instability caused by the mechanics of the arm and the higher muscular torque needed to begin the movement. Thus, the movement would be performed with greater trajectory despite the decrease of muscular torque during shoulder flexion. Due to the instability, the infant must do more adjustments to reach the object and the movement would be performed with longer trajectory, longer duration and lower velocity.

The current longitudinal study extends the Savelsbergh and Van der Kamp's (1994) cross-sectional study and provides further information about the effect of intrinsic and extrinsic factors on reaching. In addition to this, it effectively demonstrates the complexity of the developmental process of reaching skills among infants aged from 4 to 6 months.

2. Methods

2.1. Participants

Four healthy infants participated in this study: one boy and three girls, all born at full term (gestational age $M=40.33$ weeks; S.D. = 0.58 weeks) with an Apgar score of greater than or equal to 8 at the first and fifth minutes. They were evaluated longitudinally, at the ages of 4 months ($M=4$ months; S.D. = 3 days), 5 months ($M=5$ months and 1 day;

S.D. = 1 day) and 6 months (M = 6 months; S.D. = 2 days), with a tolerance of plus or minus 7 days allowed for each monthly evaluation. The current study was approved by the Research Ethics Committee (protocol no. 092/2002) of University Federal of São Carlos (UFSCar), Brazil. Informed legal consent was obtained from the participants' parents prior to the study.

2.2. Materials and procedures

"Pearl" type spherical markers were affixed to the infant's wrist (dorsal region of the carpus) using double-sided hypoallergenic tape (Out et al., 1998). Next, the infant was positioned in a "baby chair" at an inclination of 70° to the horizontal (Carvalho, Tudella, & Barros, 2005; Von Hofsten, 1982, 1984). The chair was set at the center of a calibrated volume (0.480 m × 0.320 m × 2.300 m). A 20-s interval was allowed for the infant to get used to the body orientation. During this time no stimulus was presented. Three different toys were used as objects to reach for. All of them were small and of varied shapes. The first toy was offered at a distance corresponding to the length between the infant's shoulder and wrist (Corbetta, Thelen, & Johnson, 2000; Van der Fits & Hadders-Algra, 1998). After the reach, the toy was taken away carefully and presented again for a 2-min period. The same procedure was repeated with the second toy. If the infant showed no interest in any of the toys, it was replaced by the third toy. This evaluation was repeated in the supine position (0°). The sequence of the positions was chosen at pseudorandom. The total time of the experiment was 8 min and 40 s. No strict hand position was imposed to avoid interfering with the movement biomechanics.

The whole experimental phase was filmed using three digital cameras (with a frequency of 60 Hz), one positioned above and behind the chair, the other two in front of and diagonally to the chair, one on the right side and the other on the left side, such that all the markers were visible throughout the reaching movements (Carvalho et al., 2005).

The images from the three cameras were picked up by an image capture board. The kinematic analysis of the reaching images was carried out, frame by frame, via the Dvideow system (Barros, Brenzikofer, Leite, & Figueroa 1999). The images from the cameras above and on the right side of the chair were used to analyze the movement of the infants' right arm; while the images from the cameras above and on the left side of the chair were used to analyze their left arm.

The Dvideow system output X, Y and Z coordinates from the markers fixed to both wrists for each frame of the movement. The Matlab 6.0 program was used to filter these outputs. A fourth-order Butterworth filter with a cutoff frequency of 6 Hz was used. Duration of reaching, straightness index, deceleration time and mean velocity were calculated by means of routines.

2.3. Description of dependent variables

Several variables that indicate the spatial parameters (e.g. the straightness index), temporal parameters (e.g. duration, deceleration time) and spatio-temporal parameters (e.g. the mean velocity) of the reach were analyzed.

We considered as "reach" only when the arm movements resulted in a touch of the toy with the infant's hand, at any time of its trajectory. The beginning of a reach was defined as the first frame when the infant's arm began uninterrupted approach toward the object. The end of a reach was defined as the first frame when the infant's hand touched the object (Corbetta & Thelen, 1996; Fallang et al., 2000; Rocha et al., 2006; Thelen, Corbetta, & Spencer, 1996).

The frequency of reaching was calculated as the number of reaching movements considered valid in each body orientation over a period of 4 min.

The duration of reaching was calculated as the difference in time between the start of the arm movement and the touch of the toy.

The straightness index indicated how many times the infant reached for the object through a trajectory greater than the minimal possible distance traveled by the hand. It was calculated as the ratio between the minimal distance that could have been traveled (distance between the initial position of the hand and the object) and the actual distance traveled by the hand. A straightness index of 1 indicates that the infant performed a reaching through the shortest possible trajectory (Coelho, 2004; Thelen et al., 1996).

The deceleration time indicates the time necessary for the infant to decelerate the arm movement so that his hand touches the toy. This period of the duration was measured from the time of appearance of the peak of velocity to the end of the reach (Pryde, Roy, & Campbell, 1998). A smaller deceleration time indicates that the infant needs to adjust less to the trajectory.

The mean velocity was obtained by calculating the ratio between the norm of the distance traveled and the duration of reaching (Mathew & Cook, 1991), from X, Y and Z coordinates of the wrist marker.

2.4. Data analysis

Chi-Square was applied to verify possible differences in the frequency of reach among ages and body orientations. The Kruskal–Wallis test was used to verify possible differences among ages. Finally, the Mann–Whitney test was applied to examine possible differences in dependent variables between the supine and seated positions among infants of the same age. For all the analyses, the significance level used was $p \leq 0.017$, which was corrected according to the number of comparisons.

3. Results

The four infants performed 111 reaching movements in supine position and 157 in seated position, for a total of 268 movements (Table 1). Out of this, 33 were excluded for experimental errors or because of crying. Our kinematical analysis then involves 235 reaching movements.

Statistical tests were applied in order to exclude the possibility that the observed differences arose from irrelevant differences among the toys. Taking into consideration the different toys, the Kruskal–Wallis showed no differences in terms of duration of reaching ($H(2) = 0.899$; $p = 0.638$), straightness index ($H(2) = 0.528$; $p = 0.768$), deceleration time ($H(2) = 3.848$; $p = 0.146$) and mean velocity ($H(2) = 0.241$; $p = 0.886$). Thus, we are confident that our findings resulted from the infants' age and body orientations and are not affected by the characteristics of the toys used to stimulate the reach.

3.1. The effect of age on reaching variables

As to the frequency of reaching, there was a significant difference among ages ($\chi^2(2) = 12.209$; $p = 0.002$). The higher frequency was registered at 6 months in seated position (Table 1). Two infants at 6 months had a low frequency of reaching in the supine position (two and four reaching movements, respectively) as they did not tolerate this body orientation.

Fig. 1A–D shows spatio-temporal variables of reaching for each month. There was a slight increase of duration of reaching with age. However, the Kruskal–Wallis Test indicated no significant differences in relation to the age ($H(2) = 2.855$; $p = 0.240$). Straightness index was lower at the fourth month when compared with the other months ($H(2) = 17.492$; $p < 0.01$). There were no significant differences for deceleration time ($H(2) = 4.038$; $p = 0.133$) and mean velocity ($H(2) = 4.647$; $p = 0.98$) in relation to ages.

3.2. The effect of body orientation on reaching variables

There was a greater frequency of reaching in the seated position than in the supine one (Table 1). The difference among orientation was significant ($\chi^2(1) = 7.896$; $p = 0.005$).

Fig. 2A–D shows spatio-temporal variables of reaching for each orientation at the same age. The duration of reaching was higher at the supine position for 4 and 5 months. However, Mann–Whitney test indicated significant differences in relation to the 4 months ($U(1) = 179.5$; $p = 0.001$) and no significant differences for 5 months ($U(1) = 935.5$; $p = 0.154$)

Table 1
Frequency of the reaching movements for each age (4-, 5- and 6-month-old), in supine and seated positions

	Supine	Seated	Total
4-month-old	23	41	64
5-month-old	55	55	110
6-month-old	33	61	94
Total	111	157	268

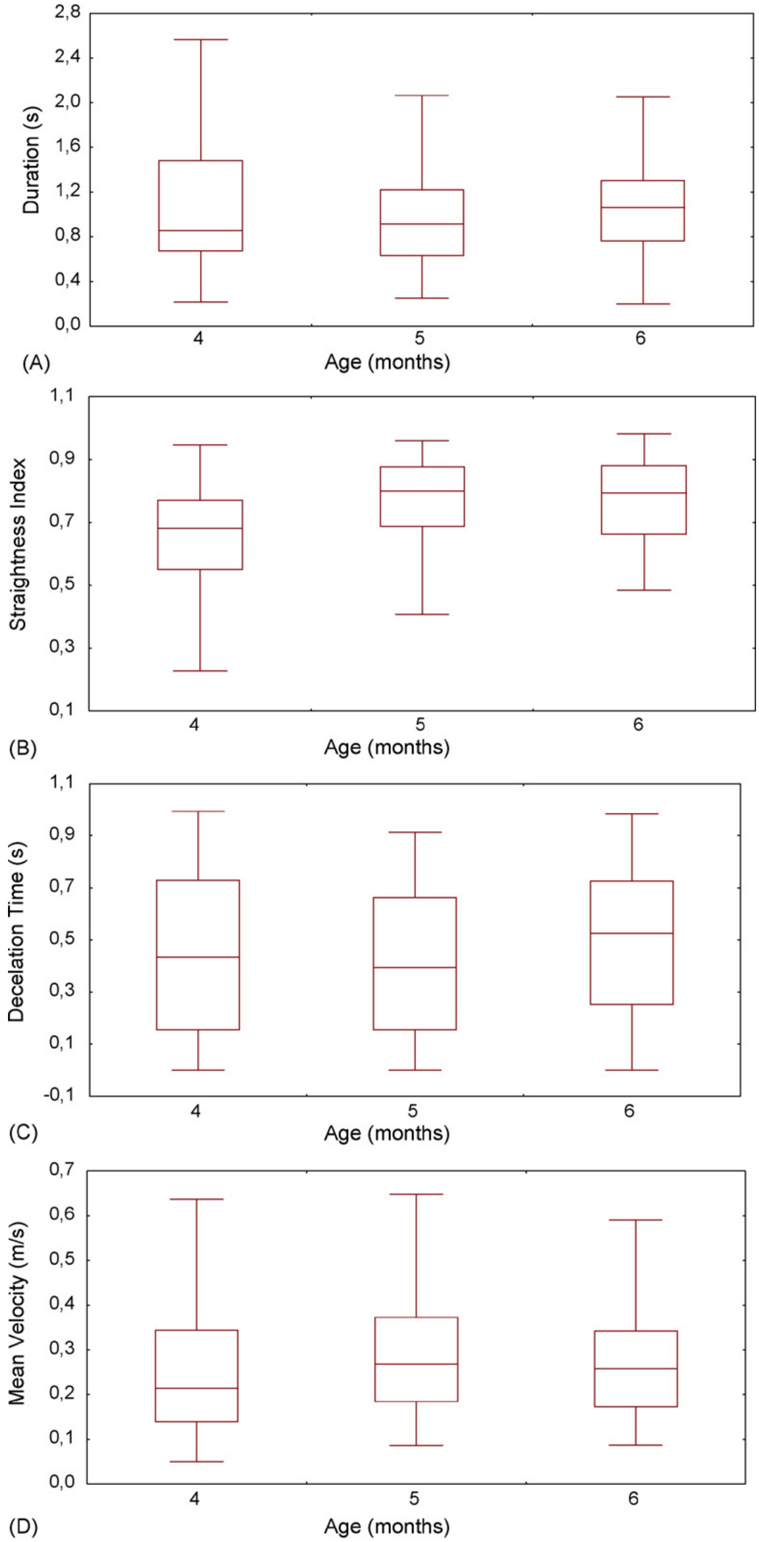

Fig. 1. Median and standard deviation of the duration (A), straightness index (B), deceleration time (C) and mean velocity (D) of reaching for 4-, 5- and 6-month-old infants.

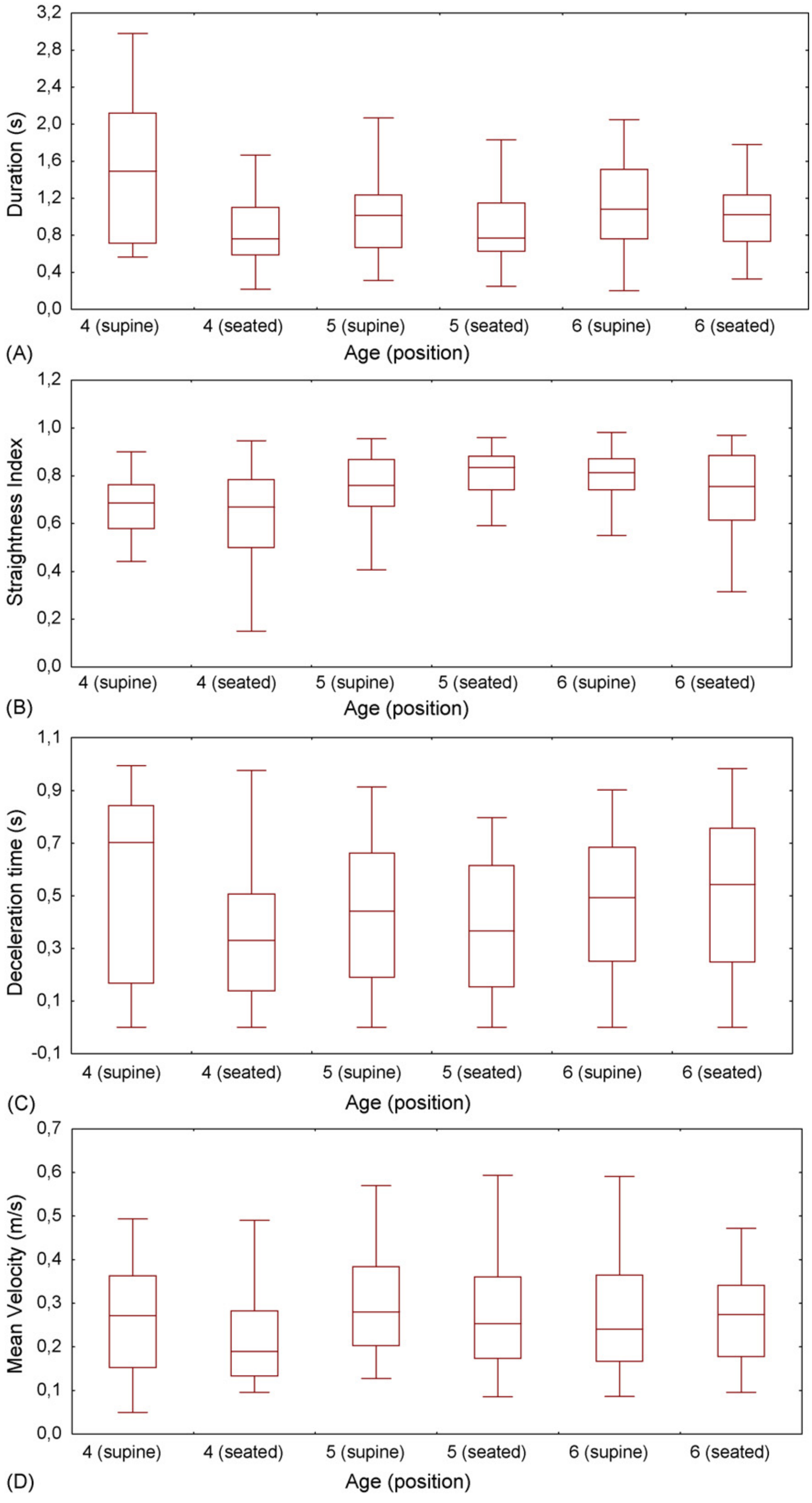

Fig. 2. Median and standard deviation of the duration (A), straightness index (B), deceleration time (C) and mean velocity (D) of reaching for supine and seated positions at 4, 5 and 6 months.

and 6 months ($U(1) = 724$; $p = 0.302$). Although the straightness index was higher for the seated position at 5 months and lower in the supine position at 6 months, there were no significant differences in this aspect for infants of 4 months ($U(1) = 348$; $p = 0.733$), 5 months ($U(1) = 862.5$; $p = 0.049$) and 6 months ($U(1) = 751$; $p = 0.432$). Deceleration time was longer for the supine position at 4 months ($U(1) = 214.5$; $p = 0.009$), and there were no significant differences for 5 months ($U(1) = 965.5$; $p = 0.229$) or 6 months ($U(1) = 783.5$; $p = 0.625$). There were no significant differences for mean velocity in relation to positions for 4 months ($U(1) = 288$; $p = 0.172$), 5 months ($U(1) = 995$; $p = 0.326$) and 6 months ($U(1) = 781.5$; $p = 0.612$). In summary, there were significant changes in duration and deceleration time, which both were longer in supine position at 4 months.

4. Discussion

The experiment examined the effect of body orientation with respect to gravity on the spatio-temporal parameters of reaching in 4–6 month-old infants. Our results indicated that age and body orientation have an influence on reaching at this stage of infants' development. Thus, we suggest that both intrinsic and extrinsic factors might affect the reaching.

As to our first hypothesis about the changes on the kinematic pattern of reaching throughout the ages in question, our findings demonstrate an increase of frequency of reaching and straightness index. The effect of age on the frequency of reaching have been described (Konczak & Dichgans, 1997; Out et al., 1998; Rocha et al., 2006; Savelsbergh & Van der Kamp, 1994; Thelen et al., 1996) and suggest that the infants improved their abilities to reach for objects with increasing age. Unexpectedly, our research indicated that the frequency of reaching in the supine position at 5 months was higher than at 6 months. Two infants had a frequency of reaching of 2 and 4 at 6 months in the supine position, though the same infants, at 5 months, had reached the object 18 and 12 times, respectively. This result may be due to the fact that, at 6 months, these infants had already a good postural control when seated, and therefore preferred to stay in this position.

The changes in straightness index indicate that infants stabilize their reaching trajectory with increasing age. The lowest straightness index (therefore, that with the longest trajectory) was observed in 4-month-olds. This indicates that the reaching strategy of infants becomes smoother and more controlled movements with age (Von Hofsten, 1991).

According to Newell (1986), the improvement in reaching ability throughout the months results from the interaction between intrinsic and extrinsic constraints. The development of reaching may arise from changes in intrinsic constrains, which follow a developmental adaptive sequence. These changes are characterized, for example, by increase in visual accuracy, cognitive ability, muscular and physical strength, postural control and perception of the surrounding world. According to Gibson (1988), the perception guides human actions, and the actions may be informative. When an infant is between 4 and 6 months old, s/he has carried out many arm movements, many of those are reaches. Consequently, the affordances from the environment changed because infants had new opportunities to acquire information through their actions. Hence, we assert that the better perception an infant has about the affordance of an object, the more accurate his coordinated reaching movement will be.

Turning now to our second hypothesis about the changes on the kinematic pattern of reaching as a function of body orientation, our findings demonstrate that the seated position allows better reaching at 4 months, an observation reflected by a notable increase in the frequency of reaching and a decrease in duration and deceleration time. As soon as the infants learn to reach, they have two central problems to resolve. Those problems are: (1) the arm's tendency to oscillate (Out, Savelsbergh, Van Soest, & Hopkins, 1997) and (2) the production the certain amount of torque in the presence of unknown external torques, such as gravity (Konczak, Borutta, & Dichgans, 1997). These problems increase when the infant is in supine position because higher muscular torque in the beginning of movement is necessary, and gravity amplifies the arm oscillation. Infants need to develop strategies to solve these intrinsic and extrinsic constraints.

Our findings suggest that the infants at 4 months change the temporal parameters of reaching to adapt to these constraints. In other words, the infants develop a strategy to increase the temporal parameters (duration and deceleration time) of reaching in supine position. Thus, they have more time to process and use the visual information to touch the toy. The model of control that the infants used does not appear to be by feedback as we did not find differences in the straightness index among positions of 4-month-olds. If the infants had used the feedback control, they corrected the trajectory of reaching after error, and it could have increased the trajectory of movement. Thus, the infants did not correct the movement after error but during its execution. According to Out et al. (1998), the differences between supine and seated positions may be caused by feedforward control used during reaching. In supine position, small errors in this control may result in missing the target and, accordingly, in a decrease of reaching frequency.

We used age as an independent variable and considered age as an intrinsic constraint. However, it is known that reaching behavior does not start at the same age for every infant (Wimmers, Savelsbergh, Beek, & Hopkins, 1998) and the experience with regard to the task within one age range (e.g. 4 weeks) can differ significantly. Therefore, in future research, it could be useful to take 'reaching experience' into account to explain the observed behavior.

At 5 and 6 months the body orientation did not have an effect on any of the examined parameters. We believe that after sufficient reaching experience and the improvement of motor abilities to control and coordinate arm movements, infants can resolve the problems related to the instability of arms and higher muscular torque in the beginning of reaching in supine. Therefore, different orientation cannot affect the spatio-temporal parameters of reaching because the infants are able to resolve these biomechanical problems. However, according to Konczak et al. (1997), 4–6 month-old infants experience problems producing the necessary torque in the presence of unknown external torques, such as gravity. A potential explanation is that this might have occurred because the total control over motricity of arm is not the only responsible agent in the gradual development of an accurate reaching pattern. Different body orientations are not the only factors that influence the spatio-temporal parameters of reaching. Other factors include improvements in visual acuity, eye-hand coordination (Bushnell, 1985), cognition (Gibson, 1988) and level of postural control (Fallang et al., 2000). The experience gained after the infant learns and practices reaching also plays an extremely important role (Galloway & Thelen, 2004; Rocha et al., 2006; Thelen, Corbetta, Spencer, Schneider, & Zernicke, 1993; Von Hofsten, 1979, 1984, 1991).

Still another possibility regarding this stability of the reaching trajectory not only at 5 and 6 months but also at 4 months is supported by Konczak and Dichgans (1997) and Out et al. (1998). These researchers also did not find differences in the reaching trajectory in the various positions. According to Out et al. (1998), the reaches of young infants are planned in terms of kinematics of movement (straightness index, radius of curvature and tangential velocity). This means that the young infants change their patterns of EMG activity to maintain the kinematics of movement. In studying adult reaching, Virji-Babul, Cooke, and Brown (1994) verified that the individuals alter their patterns of EMG activity to preserve a common movement trajectory when movements are performed under different gravitational loads. We consider that our infants planned the kinematics of their reaching (straightness index and mean velocity) in relation to different body orientations. However, our findings show that infants are still learning to control the trajectory of movement, which was verified by the changes in the straightness index among the ages. Accordingly, we suggest that the different body orientations, in regard to the gravity vector, are extrinsic constraints which do not affect the stability of trajectory and mean velocity of reaching. According to Thelen et al. (1996), infants learn first to control the movement trajectory and then learn to stabilize it against eventual movement disturbances caused by the changes in the movement's velocity. In their work, these researchers did not find significant differences in mean velocity of infants' reaching during their first year. Each new action pattern developed resulted in new movement problems that the infant must face (Rosengren et al., 2003; Von Hofsten, 2004).

As for our results, we believe that the changes in kinematics variables follow a non-linear direction since the infants changed the temporal parameters of reaching in relation to different positions at 4 months and the straightness index varied amongst all ages. According to Rocha, Silva, and Tudella 2006a, the non-linearity of development suggests that there is a connection between the infants' skills and the environmental information. Nonetheless, our findings do not conclude decisively that the development of reaching is non-linear, and that the intrinsic and extrinsic constrains (infant's skill level and environment) are responsible for this non-linearity. Further studies should be carried out to examine this question.

We conclude that the infants changed their strategies of reaching to adapt to environmental constraints. Our findings show that the development of reaching are influenced on both intrinsic and extrinsic constraints. Depending on the intrinsic constraints (e.g. the relationship between age and development) available, the extrinsic constraints (e.g. different body orientations) will influence the spatio-temporal parameters of reaching in a different way. Therefore, we emphasize that when examining developmental changes in reaching behavior, the infant's body orientation should be taken into account.

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